Scoping Study for a 6Li-Doped Scintillator Array for Fission Correlation Measurements

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2024 Annual NCSP Technical Program Review
February 20-22, 2024

LLNL-PRES-860310
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

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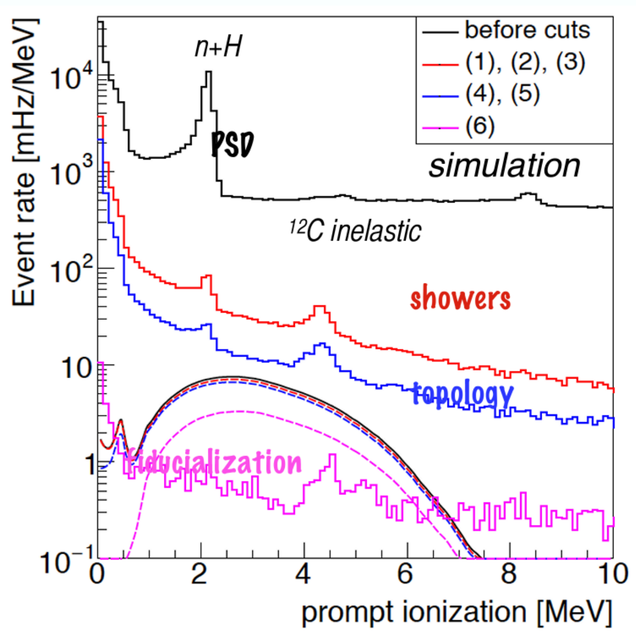
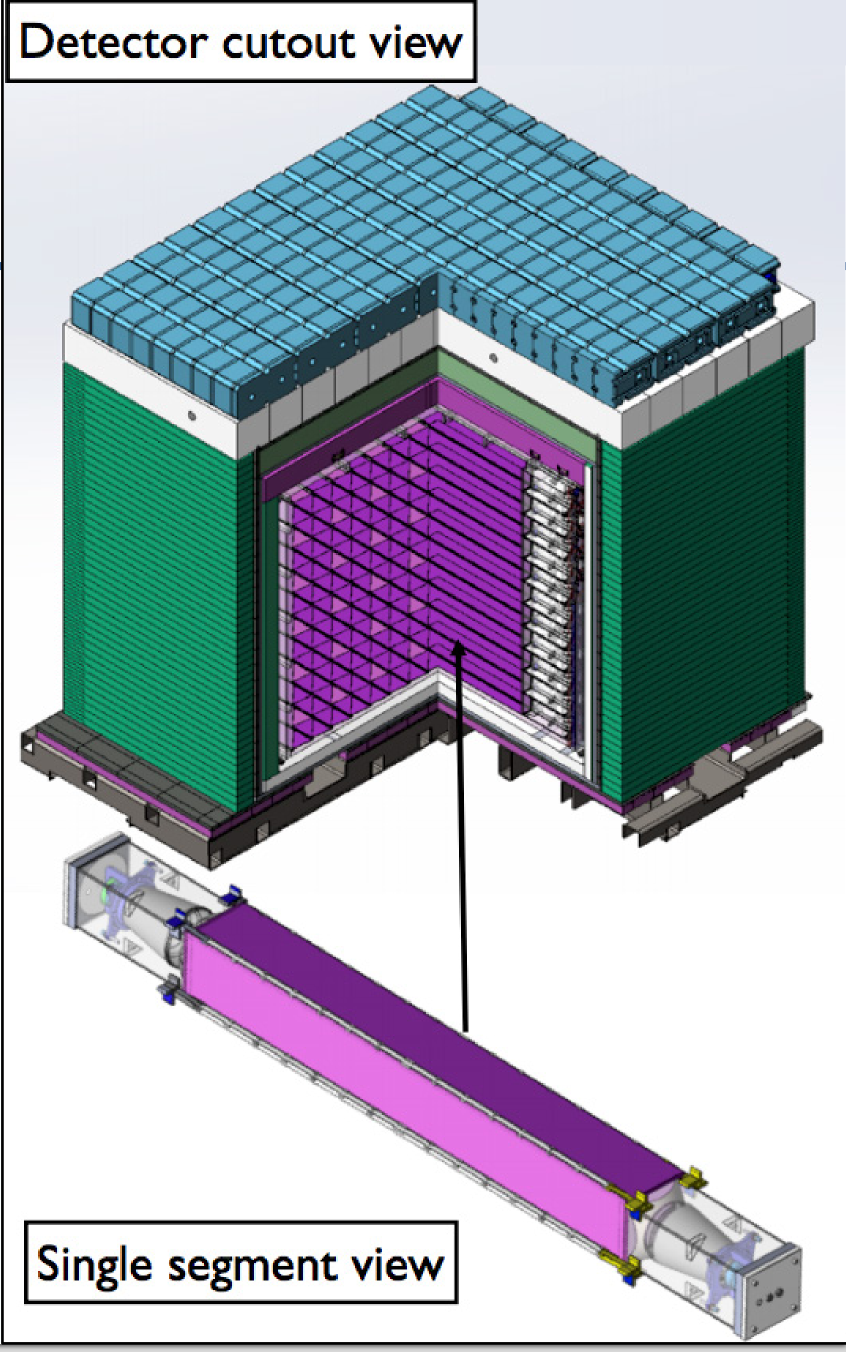
Goal: Fission Correlation Measurements

- Fission events produce a varying number and energy of neutrons and gamma rays in addition to fission fragments.
- A 4-Pi detection system could measure all neutrons and gamma rays from a fission event.
- This data would support correlation studies of neutron and gamma direction and energy.
- Couple with an incident neutron beam allows for correlation studies to include the incident neutron direction and energy.

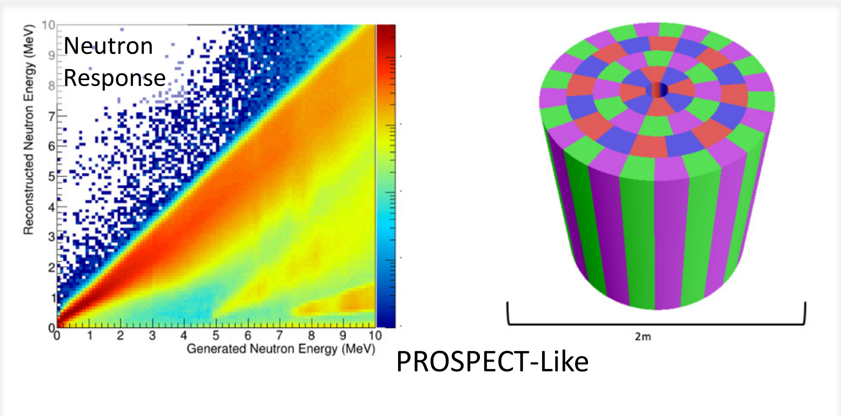
Motivation: PROSPECT-like detector

- Designed for neutron/positron measurement
- Optical Segmentation
  - Single scintillator volume
  - Low-mass optical reflector lattice for segmentation
  - Dual ended PMT readout
- Pulse shape discriminating (PSD) liquid scintillator
  - Doped with ^6Li
  - non-flammable, non-toxic
- Full PMT waveform readout
- Good energy resolution (~5% @ 1MeV)
- 3d position resolution
- Excellent background rejection
- Designed for IBD detection
  - Prompt positron
  - Delayed (~40 μs)neutron capture

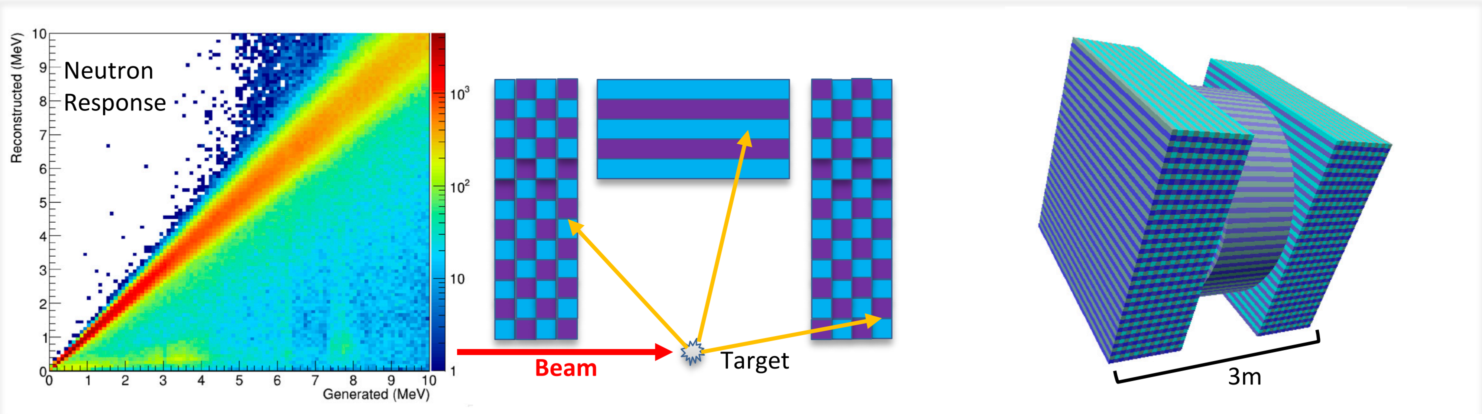




Detector Design Evolution: Hybrid Time-of-Flight Calorimeter



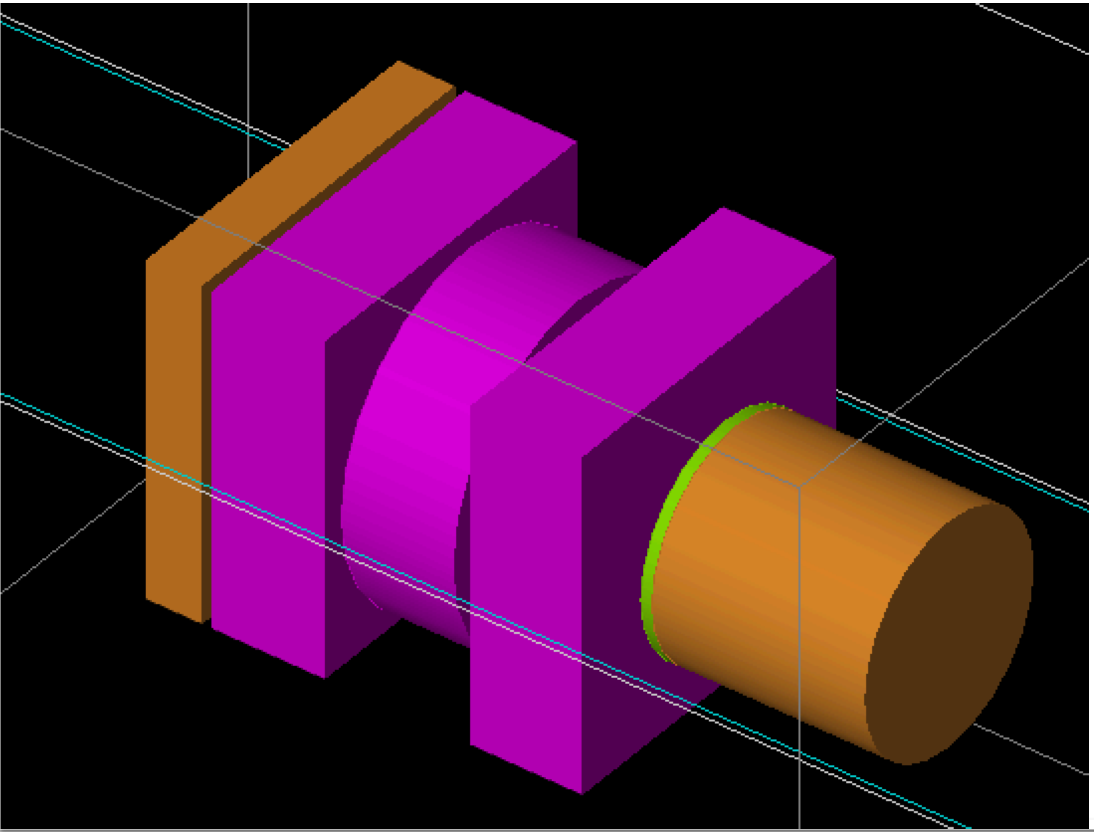
- This study uses infrastructure inherited from a similar scoping study to use this style of detector for neutron scattering experiments on actinides.
- Neutron energy resolution from scintillation was asymmetrical and broad.
- The detector design was reconfigured to include a time-of-flight cavity for neutron energy determination.

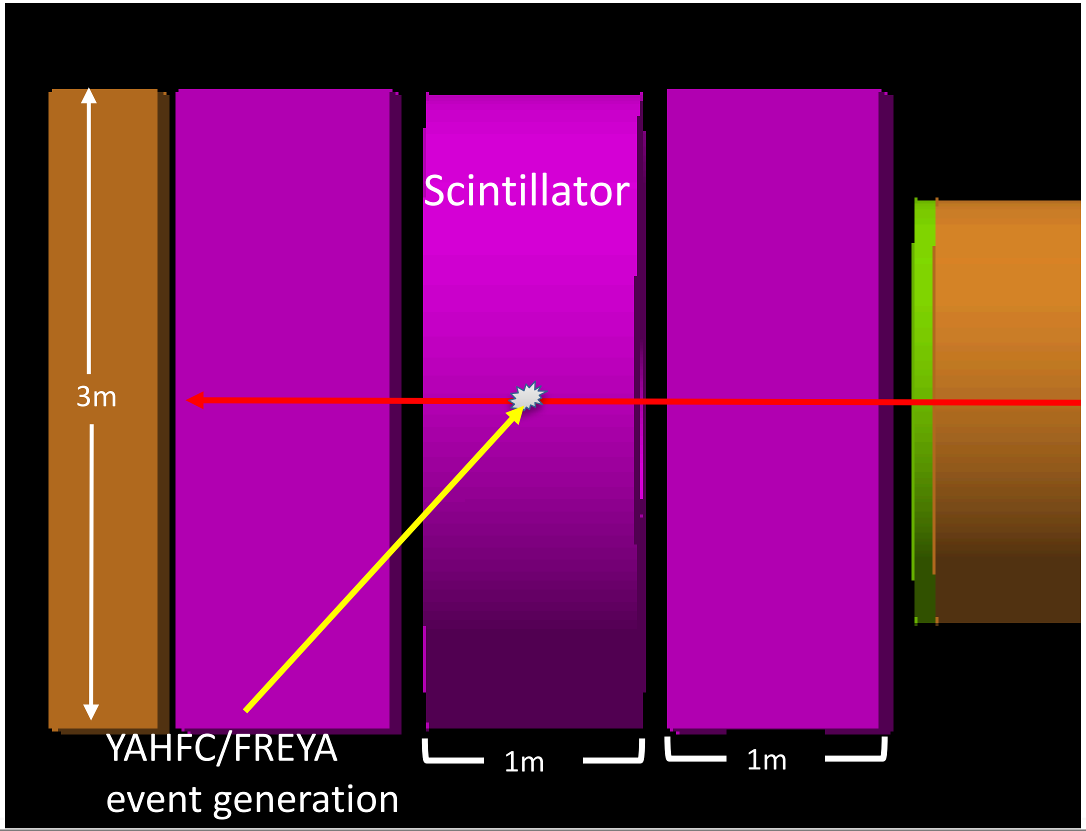


- This design requires knowledge of the time of fission for time-of-flight determination.
- Gamma energy measurements are still determined from the scintillation signal.

Simulation Geometry

- Simulated experiment requires a pulsed mono-energetic neutron beam
- Monolithic scintillator volumes are procedurally segmented in post-processing to allow for segmentation size studies.





Creating a "Realistic" Detector Response and Analysis

- Geant4 Simulation
  - Based on PROSPECT simulation code
  - Output file contains individual ionization energy deposits in the scintillator volume
  - YAHFC/FREYA generators for signal generation

- Detector Segmentation
  - Algorithmically generates the segmentation scheme of the scintillator.
  - combines energy deposits within the same virtual segment within a trigger window into a segment response.
  - Detector response smearing applied at this step based on the PROSPECT detector response.

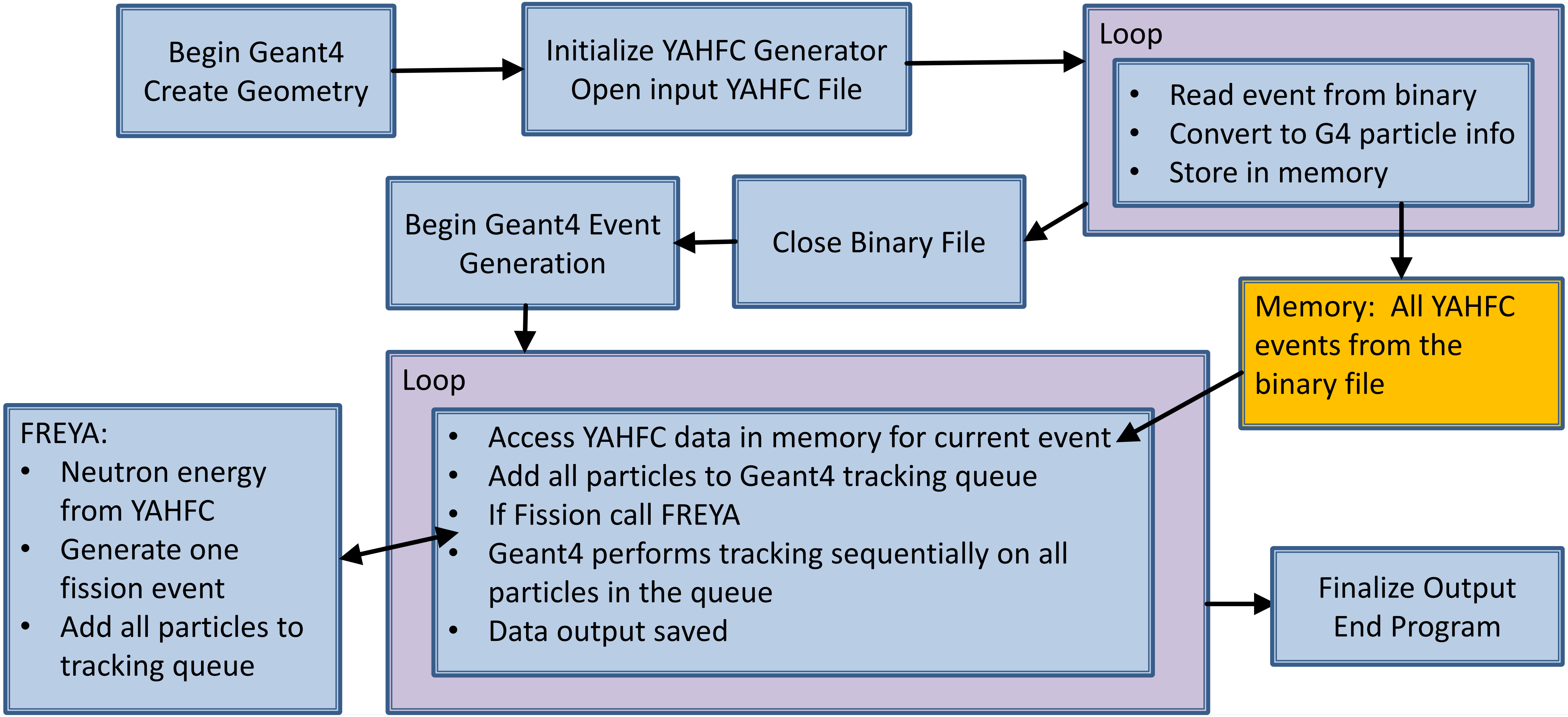
- Particle Reconstruction
  - Attempt to combine segment responses together that are from the same particle to generate a particle list for an event.
  - Only variables with detector response applied used at this step
  - Multiple variations

- Reaction channel identification
  - Using the event particle list, determine whether the event was fission, scattering or background.
  - Multiple analysis variations of this step

YAHFC Generator with FREYA Flowchart

YAHFC
Ormond, W. E. [Online] 2021. https://www.osti.gov/servlets/purl/1808762.

FREYA
Detailed modeling of fission with FREYA. **Vogt, R and Randup, J.** s.l. : NIM A, 2020, Vol. 954.



Detector Response and Particle Identification

Segmentation

- Approximate segment cross-section distance is provided to an algorithm which subdivides the scintillator volumes
- Energy deposits within a segment, occurring within the trigger window (500 ns) are summed into a segment response
- Photo-statistic smearing is applied based on the PROSPECT detector
- All "measurable values (longitudinal position, time, PSD et…) have detector response smearing applied.

Chain Particle Reconstruction

- Each segment acts as an independent detector providing position (X,Y,Z,T), PSD value and scintillation response.
- Algorithmic method based on particle kinematics to group segments into particles.
- Steps through segments in time and calculates physics values based on segment energy position and hit time.
- Improved accuracy of neutron and gamma response, particularly for many particle events (fission) over PROSPECT-like analysis.

Results: Reaction Channel Discrimination

The reaction channel discrimination analyses use the particle identification outputs to determine which type of neutron/actinide interaction occurred.

Current Variable Inputs:
Neutron Multiplicity
Gamma Multiplicity
Total neutron energy
Total gamma energy
Segment multiplicity
Incident neutron energy

Results are given for [1.0 MeV incident neutrons, 5.0 MeV incident neutrons], the other incident energies fall within the range

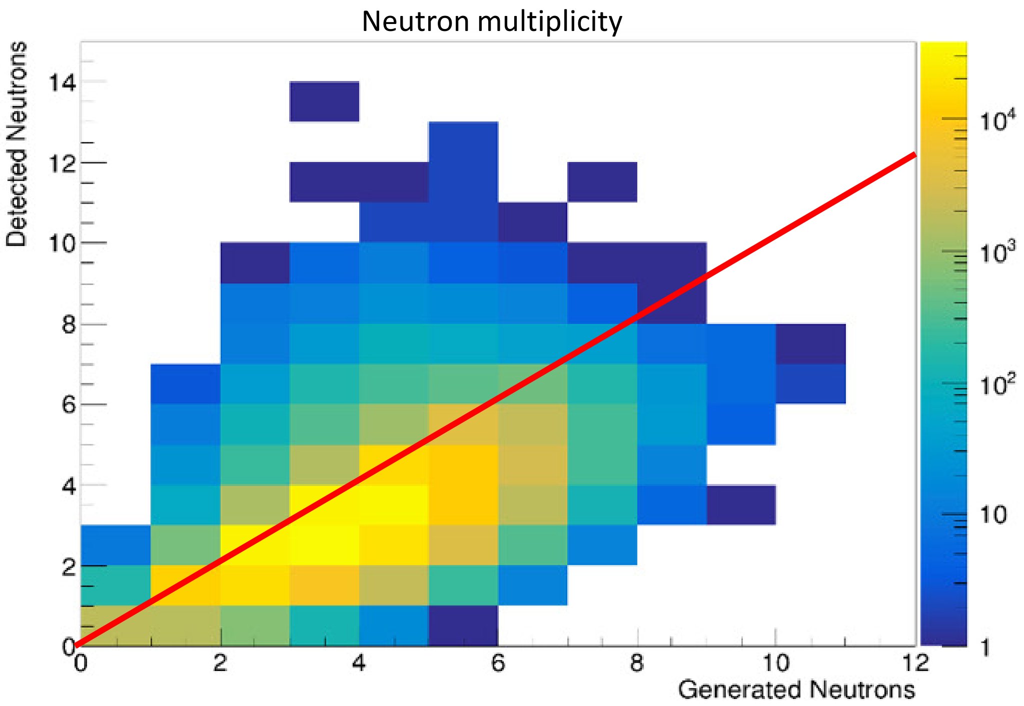
Fission:	Correct	- Analysis [97.8%, 98.4%]	Machine Learning [100.0%, 99.4%]
	Scattering	- Analysis [0.0%, 0.4%]	Machine Learning [0.0%, 0.6%]
Elastic:	Correct	- Analysis [90.8%, 89.5%]	Machine Learning [79.3%, 69.5%]
	Inelastic	- Analysis [7.8%, 5.2%]	Machine Learning [20.7%, 30.5%]
	Fission	- Analysis [0.4%, 3.8%]	Machine Learning [0.0%, 0.0%]
Inelastic:	Correct	- Analysis [49.2%, 65.7%]	Machine Learning [66.3%, 57.0%]
	Elastic	- Analysis [35.1%, 21.8%]	Machine Learning [30.4%, 16.8%]
	Fission	- Analysis [1.1%, 3.7%]	Machine Learning [3.6%, 26.2%]

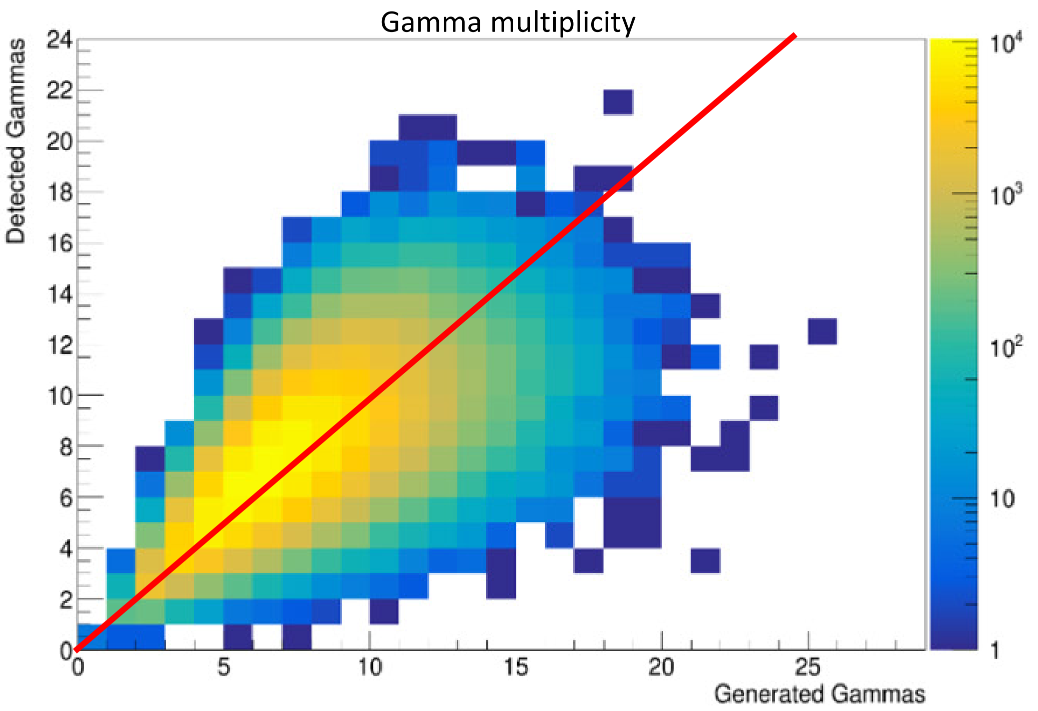
* Machine learning has not been trained with background model included

Fission Simulation Analysis: Multiplicity

- Events with the fission determination are then analyzed to compare the measured correlations to the generated correlations.

- The analysis compares the average detected multiplicity as well as the event-level detected multiplicity to the truth information





Results: Does ^{6}Li, Provide Improvement when Measuring Neutron Multiplicity?

- ^{6}Li-loading increases material and scintillator production costs, but provides a strong neutron capture signature with PSD.

- PROSPECT scintillator targeted 0.1%, in actuality was ~0.08% ^{6}Li.
- 0.3% loading possible with new prototype process.

- Capture on Hydrogen not considered for this analysis

^{6}Li-loaded liquid scintillators produced by direct dissolution of compounds in diisopropylnaphthalene (DIPN)

N.P. Zaitseva, M.L. Carman, M.J. Ford, A.M. Glenn, Ch. Roca, S. Durham, F. Sutanto, S.A. Dazeley, N.S. Bowden

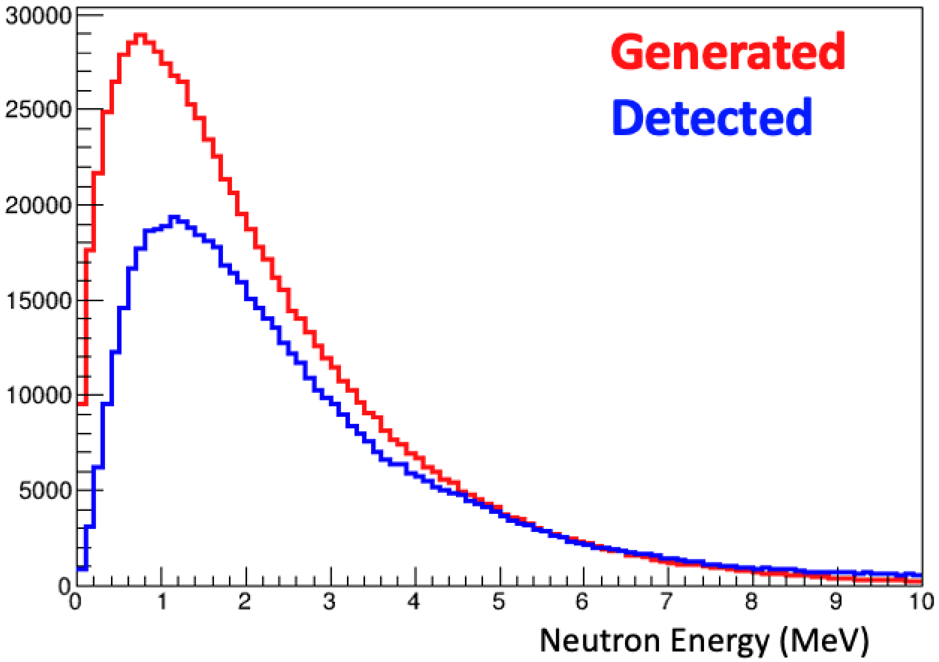
https://doi.org/10.1016/j.nima.2023.168389

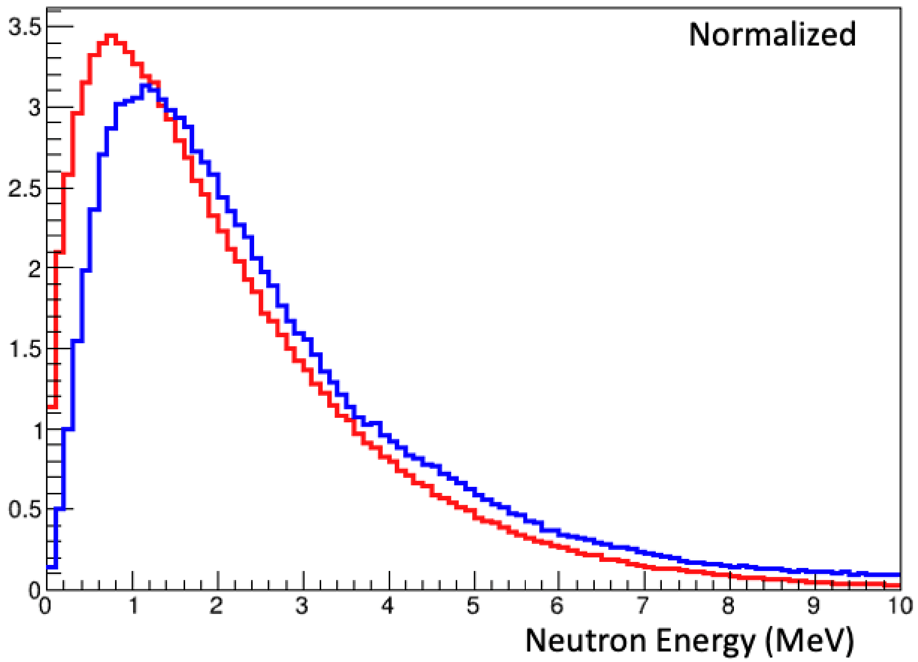
	Truth	Scatter analysis	0.1% capture	0.3% capture
Average neutron multiplicity	3.28	2.49	2.32	2.75
Correct neutron multiplicity		37%	35%	53%
Capture time constant			40.4 µs	16.9 µs
Analysis Window		200 ns	120 µs	50 µs

Fission Simulation Analysis: Neutron Energy

Neutron energy is measured through time-of-flight based on the first interaction for each detected neutron.

Energy dependent neutron detection efficiency corrections are not applied to the detected neutron spectrum.





^{239}Pu Fission Neutron Spectra

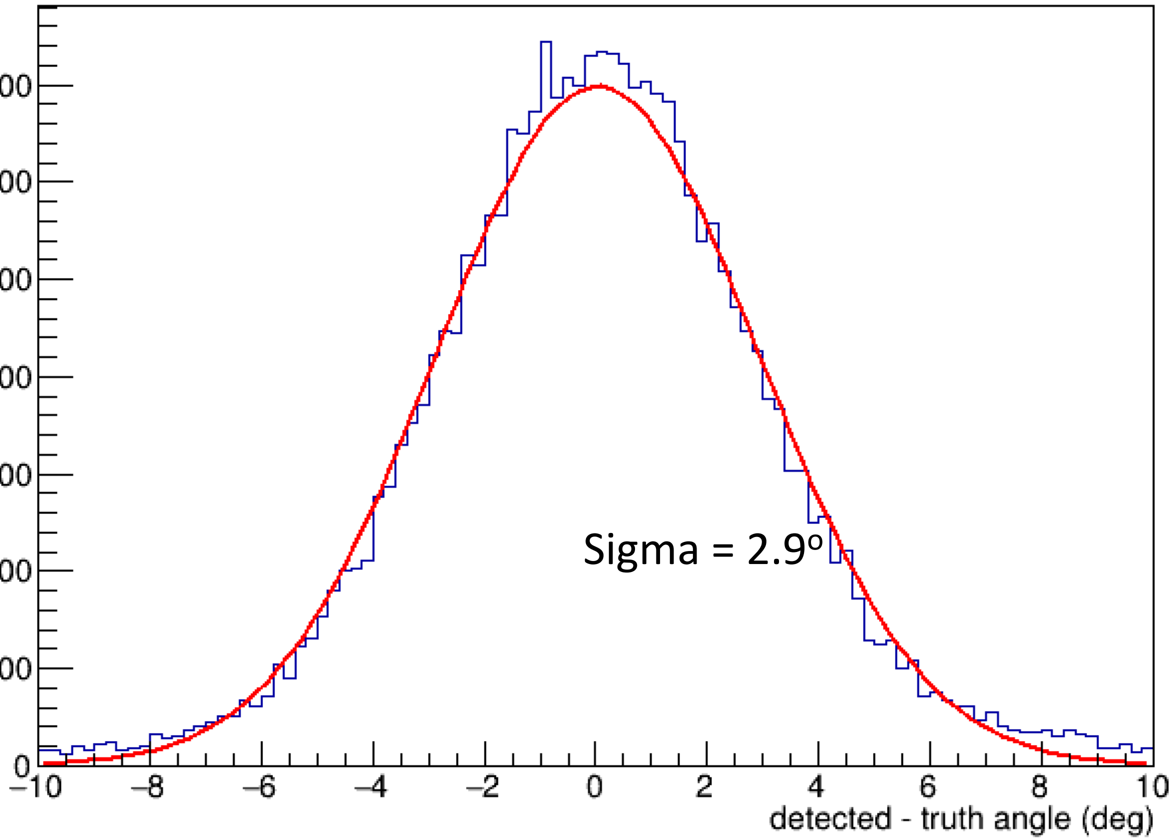
Fission Simulation Analysis: Angular Resolution

Only fission events with 2 neutrons considered for this analysis.

The true opening angle between neutrons was calculated from the simulation truth data.

The detected opening angle was calculated based on the measured position of the first neutron interaction for each neutron.

The difference between these opening angles is plotted and fit with a Gaussian function.



Difference in opening angle for 2 neutron fission detected - truth

Detector Costing Estimates

Scintillator	Amount (l)	Cost/l	Total
unloaded	18k	~$112	$2M
^{6}Li - PROSPECT	18k	~$28	$500k
^{6}Li – 0.3%	18k	unknown	unknown

Item	Quantity	Individual Cost	Total Cost
PMT	6500	$275	$1.8M
HV/Readout	1625	$800	$1.3M
Control Boxes	34	$2500	$850k
Cables	816	$7	$6k
Total			$3.2M

Conclusion

- A 4-Pi hybrid time-of-flight calorimeter would allow for full correlation analyses of fission neutrons and gamma rays.
- The required detector will be large to allow for sufficient neutron/gamma containment and the inclusion of a time-of-flight cavity for neutron energy measurement.
- ^{6}Li does not provide considerable measurement advantage compared to the costs
- This detector will likely be too expensive to justify construction for a single program.
- The additional nuclear data (scattering) obtainable however could make a collaborative project between programs attractive.

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BACKUP

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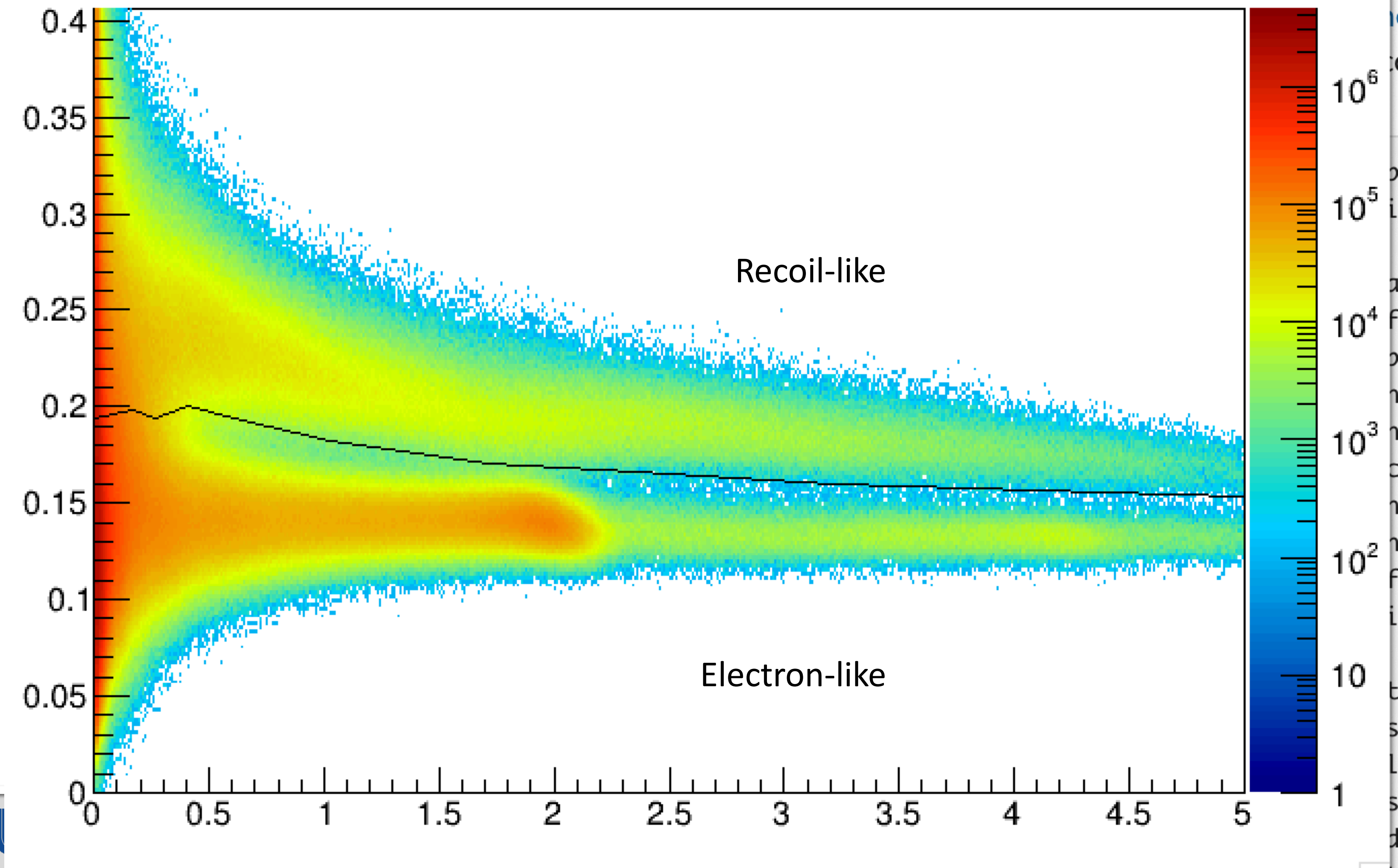
PSD – Pulse Shape Discrimination



Smeared PSD showing cut. Above the line are classified as neutron-like, below the line are classified as electron-like

Machine Learning Analysis

Python code using the scikit-learn API (scikit-learn.org).

sklearn.tree.DecisionTreeClassifier is specifically used for reaction channel classification.

Independent training datasets:

- Fission: U235 thermal fission FREYA simulation.
- Inelastic: U238 YAHFC inelastic simulation, incident neutron energy matched to test dataset.
- Elastic: isotropic mono-energetic neutrons, neutron energy matched to test dataset.
- Equal number of each channel are randomly mixed in the training file.

Test dataset: ^{239}Pu YAHFC/FREYA with elastic scatters at [1,2,3,4,5] MeV incident neuron energy.

Event by event determinations are extracted for comparison to the other analyses.

Importance of variables to the decision are given by the method to guide adjustments to other analyses.

Reaction Channels

- Elastic Scattering
  - “Billiard ball” physics, energy and momentum are conserved
  - The neutron loses minimal energy due to the vast mass difference between neutron and target
  - Measurable Quantity: 1 neutron, $E_{nf} \cong E_{ni}$
- Inelastic Scattering
  - Multiple Inelastic scattering channels, including “Quasi-elastic”
  - Some kinetic energy from the interaction is absorbed by the target nucleus, resulting in an excited state
  - The excited nucleus can emit coincident radiation (X-ray, gamma)
  - Measurable Quantity: 1 neutron, $E_{nf} < \cong E_{ni}$, gamma rays
- Fission
  - Destruction of target nucleus
  - Large release of energy with particle shower
  - Measurable Quantity: XX neutrons, YY gamma rays

Reaction Channel Determination

- Multiple analyses developed to test different methods of leveraging the information obtained from the calorimeter

- Cut Analysis: Hard cuts on particle values, particularly focused on multiplicities and energies

- Scoring Analysis: Each detector value is assessed independently, and scores are given based on the likelihood for a given channel. The channel with the highest score is the determination.

- Machine Learning analysis: All variables are fed into a machine learning classifier which determines the reaction channel for the event.

Available detector values

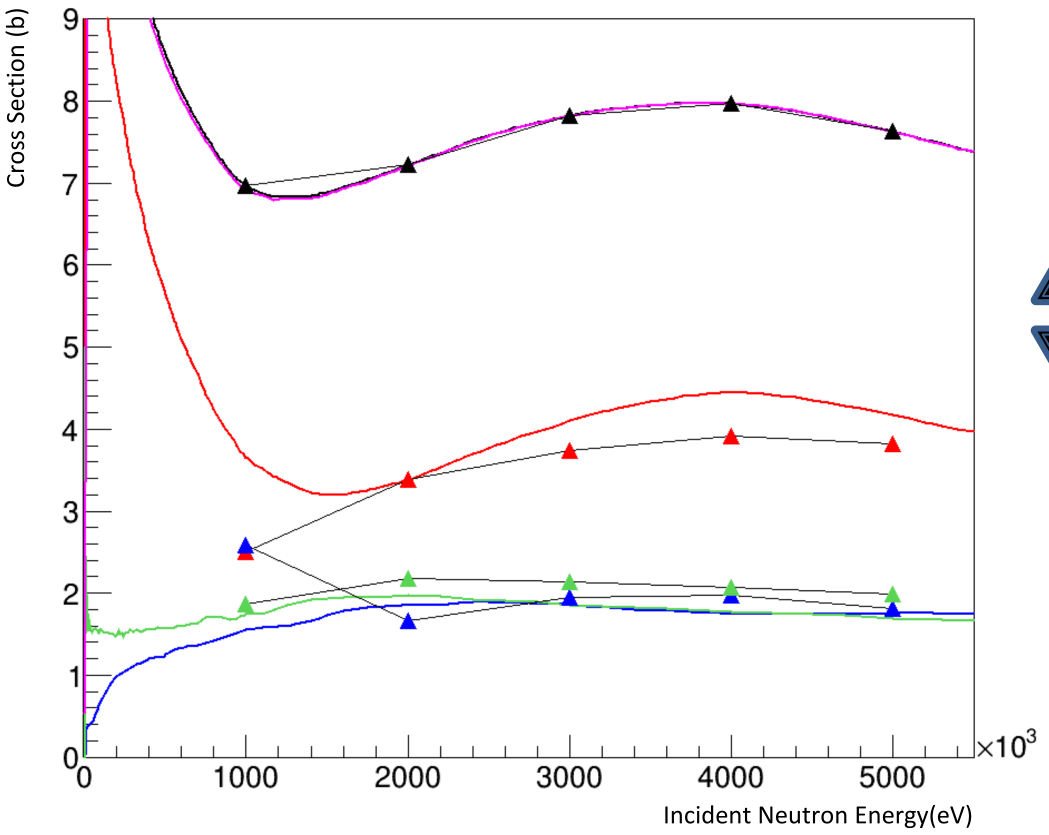
- Segment
  - Scintillation
  - PSD
  - Energy (quench corrected)
  - Time
  - Position (X,Y,Z)
- Particle Reconstruction
  - Neutron multiplicity
  - Neutron energy
  - Gamma multiplicity
  - Gamma energy
  - Time

Cross-Section Analysis

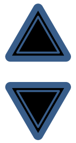
- The number of events assigned to each channel for each analysis are compared to the ENDF-VIII cross sections, as well as the number of events from each channel generated by YAHFC/FREYA.
- Currently when comparing to ENDF-VIII, event numbers are scaled so that the total detected events match the total neutron interaction cross-section.
- In addition, the number of correctly identified events and mis-identified events for each channel are compared between analyses to estimate where improvement is needed.
- The cut and scoring analyses have an additional characterization channel “Background” where events are filed if the analysis does not detect a neutron.
- The Machine Learning analysis does not yet have the “Background” category and forces all events into one of the three neutron interaction channels. This is because the ML analysis has not been trained on background data yet.

“Cross-Section” Analysis

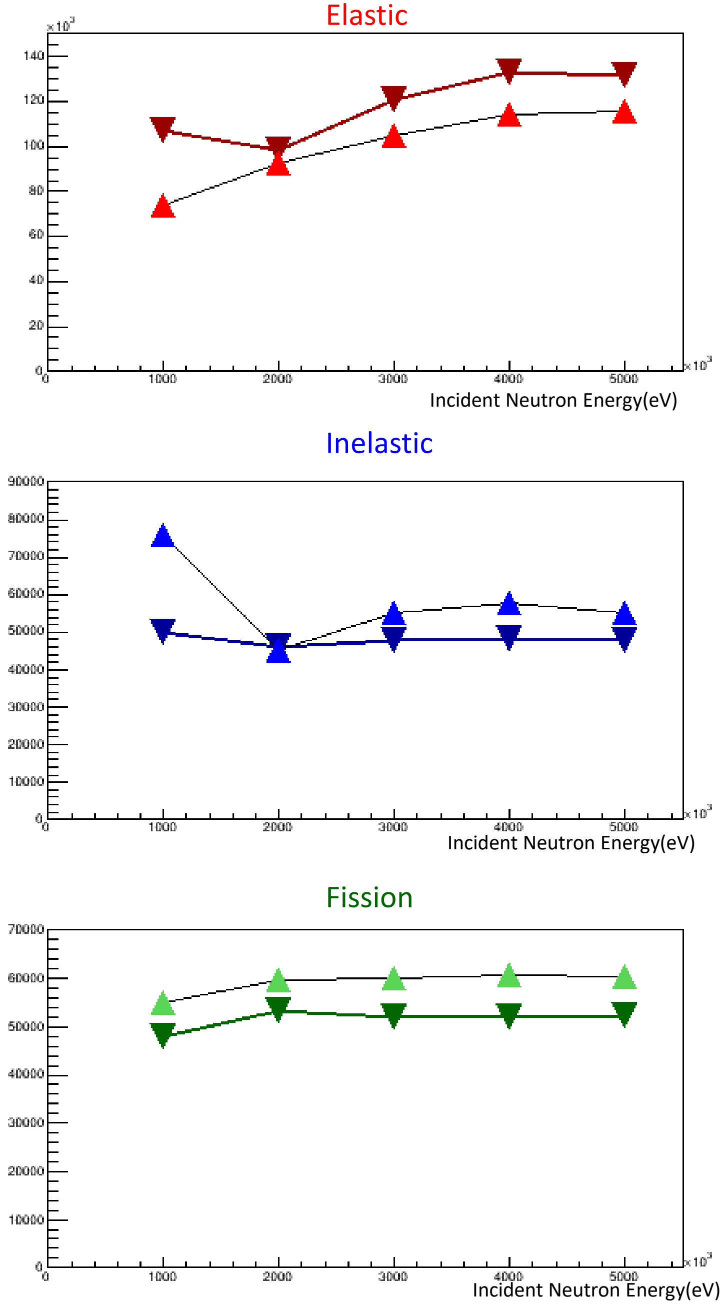
Example plots from ML analysis



Total
Elastic
Inelastic
Fission



Scaled to total cross section w/ENDF-VIII cross sections



Raw counts for each channel compared to the number of events generated by YAHFC/FREYA

Results neutron spectra

Detector neutron response spectra for each reaction channel.
4.0 MeV neutrons incident on ^{239}Pu.